CFD ANALYSIS OF FLOW PATTERN IN ELECTROCHEMICAL MACHINING PROCESS

A THESIS

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National Institute of Technology

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CERTIFICATE

This is to certify that the thesis entitled "CFD ANALYSIS OF FLOW PATTERN IN ELECTROCHEMICAL MACHINING PROCESS" submitted by Mr. SWADESH KUMAR NAYAK in partial fulfillment of the requirements for the award of **Bachelor of Technology** Degree in Mechanical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this thesis has not been submitted to another university/ institute for award of any Degree or Diploma.

Date: 11th May, 2015

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ABSTRACT

Electrochemical Machining process is a non-conventional machining process based on the Faraday's laws of electrolysis. It is an advanced machining process that has applications in fields like aerospace, medical technology etc. But still the ECM process has various shortcomings. For instance there are possibilities of passivation and boiling of the electrolyte due to complicated tool design and these results in very poor machining quality. Other problems include metal hydroxide sludge disposal etc. In the ECM process setup, the machines work in the pulsating mode and hence we don't get accurate results. Hence the CFD analysis is termed as the most accurate method to predict the flow. This project thesis aims at studying the flow pattern, current density, distribution pattern, pressure distribution, velocity profiles, turbulence etc. The required model was first designed in the CATIA software and then ANSYS –FLUENT software was used to analyze the problem statement.

The geometric model consists of a circular iron work piece, a L-shaped tool made up of copper and the electrolyte used is 20% brine solution. The L-Shaped tool has a hole at its top through which electrolyte flows and hits the work piece. The model was stimulated and analyzed to find out the results.

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CHAPTER-1

INTRODUCTION

1.1 OVERVIEW OF ECM PROCESS

Electrochemical Machining (ECM) is a non-conventional machining process in which an electric current is used to remove metal from the work piece. The ECM process relies on the principle of Electrolysis for the removal of the material. Michael Faraday (1791-1867) found out that if two separate electrodes are kept in a bath containing a conducting liquid and a DC potential difference is applied across them , the metal gets removed from the anode and gets deposited on the anode.ECM is useful for machining hard materials which are impossible to machine in conventional machining process. ECM process is the reverse of electroplating process. There is no tool wear in this process and the tool also does not come in contact with the work piece. In case of work pieces that have complicated shapes, knowing the machining variable’s distribution within the Inter Electrode Gap (IEG) is very difficult. So we need to understand those parameters. Once we get to know about the flow pattern, it is easy to avoid passivation and other problems encountered in ECM process. This is the main motivation behind undertaking the project. The rates of electrochemical dissolution depend strongly on the temperature. The energy losses in the gap are large but the heat can be removed by high flow of electrolyte and, thus, depends on the geometry. The main objective of this project is to study the flow pattern and know about the machining variables within the IEG.Once the flow pattern is known, it is easy to design the tool and avoid passivation.

1.2 WORKING PRINCIPLE OF ECM

ECM is the removal of the material from the work piece by anodic dissolution in an electrochemical process. In the process the work piece is the anode and the tool is the cathode. This process works on the principle of Faraday's law and Ohm's law. Both the electrodes are submerged in the electrolyte and an electric voltage is applied across these electrodes. Conduction of electricity is due to the movement of ions of the electrolyte between the anode and the cathode. Metal is removed by the controlled dissolution of the work piece when current passes through the system of arrangements. The Fig 1.1 shows the two electrodes placed close to each other and immersed in an electrolyte.

Faraday suggested two laws to be used in the process of electrolysis. These are-:

(1) The amount of chemical change produced by an electric current is proportional to the quantity of electricity passed.

(2) The amount of different substances dissolved by the same quantity of electricity are proportional to their chemical equivalent weights.

$$m = \frac{ItA}{\rho ZF}$$

The high current densities help in the faster production of gas bubbles and hydroxide sludge in the Inter Electrode Gap which act as a deterrent to the electrolyzing current after some time. Hence these end products need to be removed for maintaining a high current density over a period of time. This is made possible by circulating the electrolyte at high speed in the Inter Electrode Gap. MRR decreases with increase in the gap between the electrodes. Hence this fact should be taken into account.

1.3 CHEMICAL REACTIONS IN ECM PROCESS

Let us take a neutral salt solution of sodium chloride (NaCl) as an electrolyte. The work piece material is made up of iron (Fe). When a potential difference is applied across the two electrodes the water and NaCl undergo ionic dissolution as-

$$NaCl \leftrightarrow Na^{+} + Cl^{-}$$

$$H_2O \leftrightarrow H^{+} + (OH)^{-}$$

The positive ions Na^{+} and H^{+} move towards the cathode (tool) and negative ions Cl^{-} and $(OH)^{-}$ move towards the anode (tool). Among the positive ions H+ will take the electrons from the cathode and form hydrogen gas. Likewise iron of the work piece material gets converted into Fe^{2+} ions by using electrons and combines with the hydroxyl ions to form sodium hydroxide.

REACTIONS AT ANODE:

$Fe \leftrightarrow Fe^{2+} + 2e^{-}$

$Fe^{2+} + 2Cl^{-} \leftrightarrow FeCl_2$

$Fe^{2+} + 2OH^{-} \leftrightarrow Fe(OH)_2$

$FeCl_2 + 2OH \leftrightarrow Fe(OH)_2 + 2Cl^{-}$

$2Cl^{-} \leftrightarrow Cl_2(g) + 2e^{-}$

$2FeCl_2 + Cl_2 \leftrightarrow 2FeCl_3$

REACTIONS AT CATHODE:

$Na^{+} + e^{-} \leftrightarrow Na$

$Na + H_2O \leftrightarrow Na(OH) + H^{+}$

$2H^{+} + 2e^{-} \leftrightarrow H_2\uparrow$

$H^{+} + Cl^{-} \leftrightarrow HCl$

$2Fe(OH)_2 + H_2O + O_2 \leftrightarrow 2Fe(OH)_3\downarrow$

$Fe(OH)_3 + 3HCl \leftrightarrow FeCl_3 + 3H_2O$

$FeCl_3 + 3\ NaOH \leftrightarrow Fe(OH)_3\downarrow + 3NaCl$

The hydroxides and chlorides will form sludge and get precipitated at the bottom of the container. Hydrogen gas is evolved at the tool (cathode) and no deposition takes place there.

1.4 ECM MACHINING PARAMETERS

1.4.1 Electrolytic Flow

Electrolyte is the conducting fluid in which the tool and the work piece are submerged. It is a highly important parameter in the whole ECM process. Electrolyte is the agent that completes the electrical circuit and helps in maintaining a continuous current flow between the cathode and the anode. The electrolyte has numerous other functions like:-

1) It helps in removing the sludge deposited from the cutting region.

2) It acts as a coolant.

Insufficient electrolytic flow will result in the reduction of the material removal rate. The electrolyte used must have high electrical conductivity and low corrosiveness and toxicity.

1.4.2 Temperature Control

The temperature of the electrolyte must remain constant or else it will cause variation in the conductivity. Very low temperature of the electrolyte results in the reduction in material removal rate and very high temperature of the electrolyte may cause vaporization of the electrolyte. Hence an optimum temperature range of the electrolyte is to be used in the ECM process.

1.4.3 Inter Electrode Gap

In the electro chemical machining process, the tool and the work piece are not in contact with each other. They are separated by a small gap known as IEG (inter electrode gap).Normally in ECM, a gap of about 0.05 to 0.07 mm is kept between the work piece and the tool. If the gap between the tool and the work piece is small, it results in higher current density and hence greater material removal rate.

1.4.4 Tool Feed Rate

For greater material removal we need to have a higher tool feed rate. The rate of metal removed depends upon the proximity between the tool and the work piece. If the tool feed rate is higher than the instantaneous gap between the tool and the work piece decreases resulting in higher current density and hence higher MRR.

1.4.5 Tool Design

The tool to be used should meet some specific requirements to be used in the ECM process. The material to be used for tool making should be a good conductor of electricity. The material must be strong enough to withstand the strong hydrostatic force exerted when the electrolyte is allowed to flow through the tool in the Inter Electrode Gap. In the present scenario a L-Shaped tool is used with a central through hole through which the electrolyte passes at a high speed.

1.5 SPECIFICATIONS OF ECM

TABLE 1.1-ECM PROCESS PARAMETERS

Working gap	0.05-0.8 mm
Current density	5-100 A/cm^2
Voltage	5-30 V
Current	50-40,000 amp
Temperature	30-80 ^0C
Velocity	5-50 m/s
Inlet Pressure	0.15-3MPa
Outlet Pressure	0.1-0.3MPa
Feed Rate	0.1-20mm/min
Electrolyte Used	Brine solution, Sodium nitrate
Specific power consumption	$7w/mm^3/min$
Accuracy and surface finish	0.02 mm, 0.4µm
Application	Machining hard material
Limitation	High specific energy consumption
Mechanical properties	Stress free machining, reduce tool wear
Surface properties	No thermal damage

CHAPTER – 2

LITERATURE REVIEW

2.1 INTRODUCTION

A detailed literature review was carried out on the subject of Electrochemical Machining and it is found that the research on this subject started long way back. Some of these research works of distinguished persons have been studied and have been stated below.

2.2 LITERATURE REVIEW

Evgueny I. Filatov [1] He made research on the numerical simulation of the ECM process. He took a two dimensional part of a machine into examination .In his simulation the electrostatic force field is taken to be linear. He also assumed that of the total volume a part is taken up by liquid and the rest of the volume is occupied by hydrogen and air. To describe the electrolytic flow the equations of conservation of mass of air , hydrogen amid liquid are taken into account and also the conservation of energy was applied. Then the problem was solved by the finite difference method. At the end the effect of the unsteady technical factors on the machining accuracy was examined.

J. Kozak [2] He studied the effect of electrolytic concentration on coping accuracy of precision-ECM. The final shape and size of the work piece has to be obtained in the steady state of the ECM process characterized by various parameters like pressure at inlet, outlet etc. It is applied in the Flexible Manufacturing System. The tool motion controls the final work piece shape. His studies helped in using cost effective electrodes with irregular contours. The working area is also diminished which reduces the heat generated and hence the rate of dissolution of work piece material is more uniform.

M.M. Lohrengel et al. [3] He worked on the work pieces made up of steel. He showed that those work pieces when subjected to anodic dissolution at large values of currents (about $120A/cm^2$) and high flow rate of the electrolytes are structured in neutral $NaNO_3$ solution. Likewise if we need to identify the process and we have to find out the structure and current distribution at the work piece-electrolyte interface. All detailed information regarding the Rate Determining Step (RDS) and work piece interface are neglected.

Conner et al. [4] He researched on the PWR assemblies and gave a detailed paper on the CFD modeling methodology and validated the steady state operation in the fuel assembly. He worked on single phase and two phase flow conditions at the structural grids containing the mixing devices. Single phase flow conditions were analyzed and detailed mesh, turbulence model etc. were duly noted. In order to study the two-phase conditions in PWR assemblies, CFD models are being developed and can be presented later.

B. Bhattacharyya et al. [5] His paper threw light on analyzing the basic material removal mechanisms that was in use in the ECDM process. This helps in optimization of the machinability of ceramic materials. He emphasized on getting a greater machining rate and accurate machining. Various process parameters like temperature, inter electrode gap, voltage, concentration, type of electrolyte, electrodes etc influence this process.

T.R. Idrisov et al.[6] He proposed a new theory of work piece dissolution in electrochemical machining. In this model he used bipolar microsecond pulses at high current densities. The model takes into view the fluctuating nature of the anode and cathode potentials, change in temperature of the electrolyte, gas filling at the inter electrode gap. This theory also takes into account the preliminary reverse polarity pulse influence on the potential of the anode.

Frank et al. [7] He presented a theory on the multi phase flow models of the mono and poly-disperse bubble type of flow in the Eulerian Framework of ANSYS-CFX. The momentum transfer between the phases is taken into account in the model due to the forces governing them. In the new MUSIG Model, different gas speeds were taken into account. They depend upon the diameter of the gas bubbles and also on the different properties of the bubbles.

2.3 OBJECTIVE OF STUDY

There have been various researches regarding the various traits of the Electro Chemical Machining processes which have been undergone over the years. The material removal rate has been practically calculated and there are various limitations that go in the way of the material removal rate. All these shortcomings can be removed by getting to know about the flow patterns. Hence the main objective of the project thesis is to find out the flow patterns like temperature flow pattern, pressure pattern, turbulence etc. of the electrolyte and to find out how much inlet velocity of the electrolyte is required for a particular value of the current density to prevent the electrolyte from boiling.

2.4 SCOPE OF STUDY

The above problem has to be analyzed using the ANSYS-FLUENT software and the various flow patterns are to be studied. The electrolyte is to be pumped through a groove in the L-shaped tool and directed towards the work piece. The following Patterns are to be found out –

1) Velocity distribution

2) Pressure profile

3) Turbulence on the work piece electrolyte junction

4) Temperature distribution

5) Material Removal Rate

And the graphs and the contours are also to be plotted.

CHAPTER 3

MODELLING AND ANALYSIS

3.1 INTRODUCTION

This chapter deals with the model that has been used for the project thesis. This includes the model that has been made at the first to the analysis of the model done at the last to find out the various flow patterns and contours of the different parameters. The element selection to the different assumptions taken in this project thesis analysis has been discussed in the chapter.

3.2 GEOMETRIC MODELLING

In the present project the model to be used was first drawn in the CATIA software and modelled in it. After the modelling was completed in CATIA the model was imported in the ANSYS-FLUENT module and analyzed. In the model there is a L-Shaped tool that has a central bore at the centre along the whole length of the tool. This central bore is for the electrolyte to pass through and is 3mm in diameter. Then comes the modelling of the work piece. The work piece used in the thesis is circular in shape with 60 mm of diameter and height of 20 mm.The electrolyte that has been used for the model analysis is aqueous solution of NaCl.The model was simulated for inlet velocity of 20 m/sec.

Model- L shaped tool with a central through hole:-

The tool is a L shaped one with a central bore through the centre. The tool has a height of 50 mm and the hole has a diameter of 3mm. The long side of the tool has a length of 20 mm and the short side has a length of 15 mm.Fluid is to be flown from the top of the tool through the hole in the middle up to the work piece

.

3.2.1 SIMULATION CONDITION AND PROCEDURE

To carry out the ECM process we need a tool, a work piece and an electrolyte and we need to provide opposite charges to the cathode and anode. Here the work piece is made up of iron and the tool is made up of copper and the electrolyte used is the 20% solution of NaCl. The analysis of the flow pattern was done taking into account all the input parameters like the input velocity, current density, and all the required properties of the electrolyte like thermal conductivity, specific heat, viscosity etc. The input parameters were provided by the user. Due to the constant current flow and material removal the temperature of the electrolyte increases continuously but the increase in temperature is not taken into account in the present scenario.

3.3 MESHING

After the geometry was done in CATIA software then it was imported in ANSYS for meshing purposes. The meshing was done using the ANSYS MESH Module in the ANSYS commercial software. The quality of meshing of a model is a indication of how accurate an analysis would be. The lower the element size in a mesh the higher will be the number of nodes and the result will be most accurate. In the present model, the elements meshed were in the tetrahedral shape and the minimum element size was 0.5 mm.Tetraheral meshing is the most convenient meshing type as mesh controls can be added easily here and automatic solutions can be easily provided. The hexahedral meshing can also be used as it gives best results but it is very complex and complicated to generate. Automatic option for meshing is also available but it results in not so fine meshing.

3.4 GOVERNING EQUATIONS

In the present problem of ANSYS FLUENT two types of governing equations are used to find out the solution. First equations are the computational fluid dynamics modeling equations which are in built in the software but default and the second one is the continuity equations. The law of conservation of mass and energy also govern the above problem.

3.4.1 Computational Fluid Dynamics Model Equations

As the flow is turbulent in nature a turbulent model is required to solve the problem statement. K-ε model is a turbulent model that is used in the present model. This is a two equation model which finds relationship between the viscosity in turbulent flow and stress. In this turbulence model 'K' represents the kinetic energy with respect to speed disturbances. 'ε' represents the fastness at which the speed fluctuations are removed and is called the turbulent eddy dissipation factor. The equation 3.1 represents the continuity equation –

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \qquad (3.1)$$

The equation 3.2 is the momentum conservation equation-

$$\frac{\partial P u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = \frac{\partial P\prime}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_{eff}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j}\right]\right) + S_m \qquad (3.2)$$

The turbulent kinetic energy differential equations are used to find out the values of k and ε. The differential equations for the same are the differential equations that are differentiated to find out the values of K and ε.

3.5 ASSUMPTIONS

1) The Inter Electrode Gap (IEG) remains constant during the whole course of the process and heat is generated only in the IEG and not all around the container.

2) The electrodes in use will not change their material properties in any way during the machining process, only the electrolyte changes its properties.

3) Heating takes place only in the IEG due to the partial conversion of electrical energy into thermal energy due to joules heating effect.

4) Both the tool and work piece are homogenous and isotropic.

5) No change in current or voltage takes place during the machining process.

6) The height of the electrode is assumed to very much greater in height than the IEG's value.

7) There is no effect of the hydrogen gas that is evolved on the machining process.

8) Axis symmetric domain.

3.6 MATERIAL PROPERTIES

Materials that are being used for the given analysis of machining are copper as the tool , iron as the work piece and aqueous NaCl as the electrolyte. For the simulation process the different needed values are to be given as input.

Table 3.2 Material properties for Copper, Iron and Electrolyte

MATERIAL PROPERTY	ELECTROLYTE	COPPER	IRON
DENSITY(kg/m^3)	1050	8940	7680
CONDUCTIVITY(W/m/K)	0.8	401	80
VISCOSITY(Pa s)	0.001	----------	-------------
SPECIFIC HEAT(J/Kg K)	3760	390	460

Heat transfer coefficient between tool and work-piece = 1000 $W/m^2.K$
The inlet velocity of electrolyte is in the range of 5 – 50 m/s.

3.7 BOUNDARY CONDITIONS

In the above problem case the domains are to be specified first before specifying the boundary conditions. In the above problem 3 domains are to be specified one each for the work piece, tool and the electrolyte.so there is one fluid domain and two solid domains.

1) Thermal boundary conditions

The surfaces of the tool and the electrodes are assumed to be adiabatic in nature and hence no conduction of heat can take place between the electrodes and the electrolyte. So the temperature at the inlet is taken to be 27 degrees.

2) Electrical Boundary Conditions

The electrodes are given opposite polarities. The tool is the cathode and the work piece is the anode. Hence electrical potential difference is to be applied across these oppositely charged electrodes. A voltage of 10V and a current 100 amp was applied across the tool and the work piece for better machining rate. The current density needs to be high between the prescribed value between 5 to 20 A/cm^2.

3) Pressure Outlet Boundary condition

The gauge pressure is taken to be 0 Pascal so that the pressure does not affect the machining rate in any way.

CHAPTER -4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

After the analysis of the constructed model was completed in the ANSYS FLUENT the different working parameters of the ECM process has been explained in the present chapter with the help of graphs , contour lines, vectors etc. The variation of the different parameters like velocity, pressure, turbulent kinetic energy etc. has been found out and has been noted down in this chapter. The different residuals values vary with the number of iterations as per the following graph.

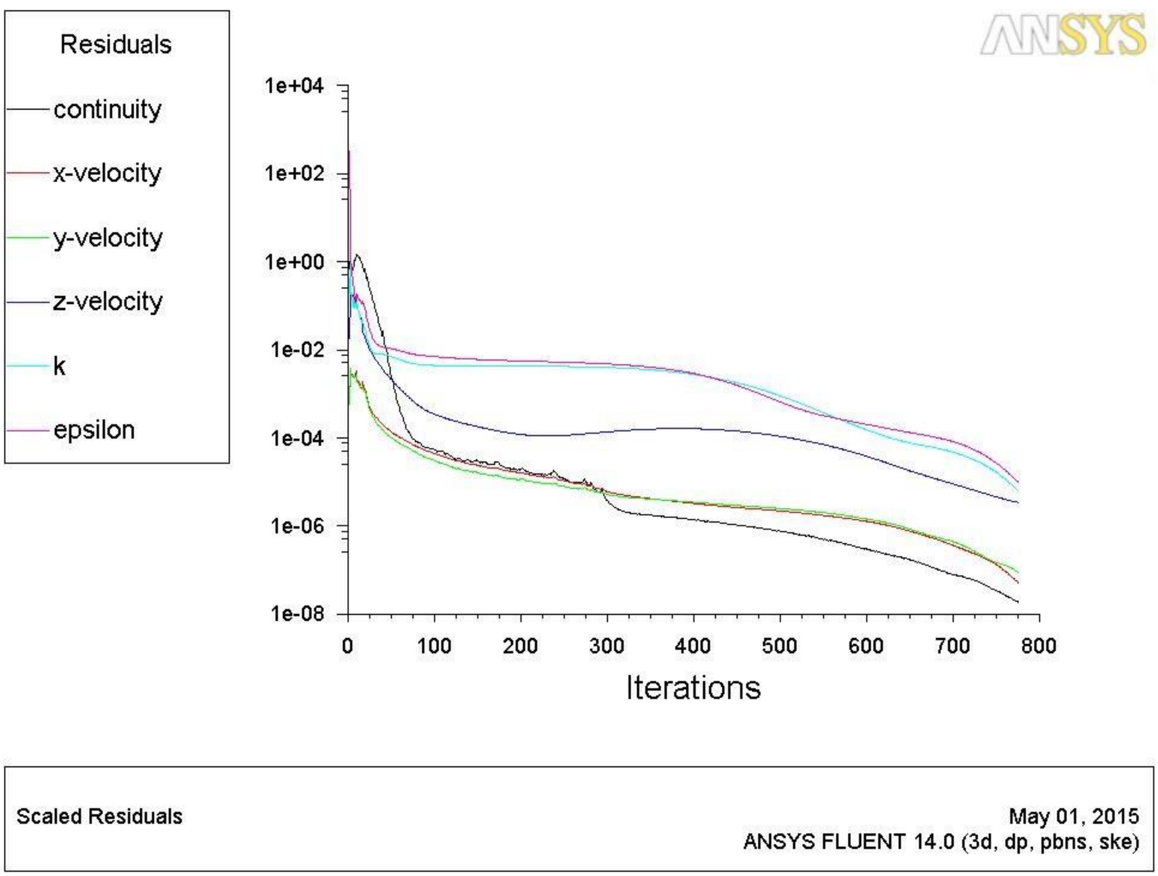

Fig 4.1 Final solution

4.2 VELOCITY PROFILES

Fig 4.2 depicts the contours of the velocity magnitude for the given model when the pressure in the inlet is 20m/sec.

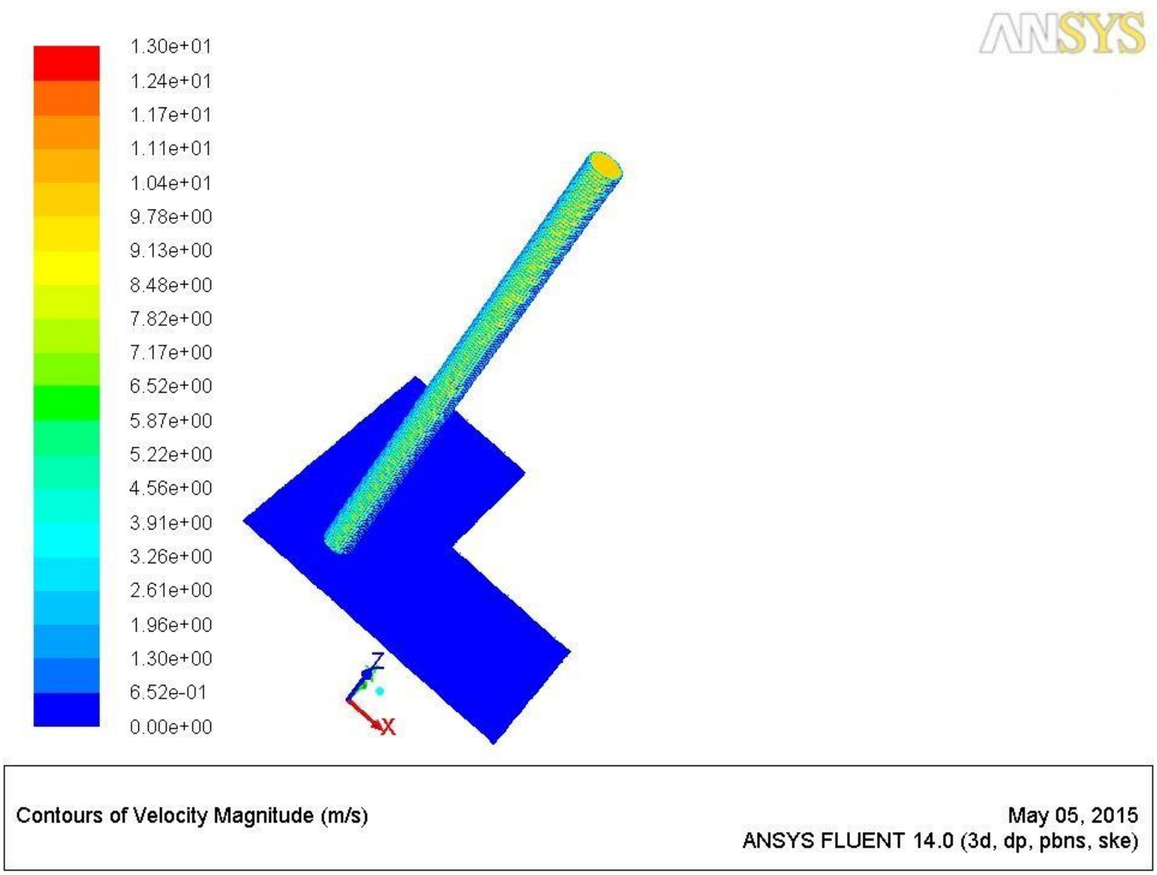

Fig 4.2 Contours of velocity magnitude

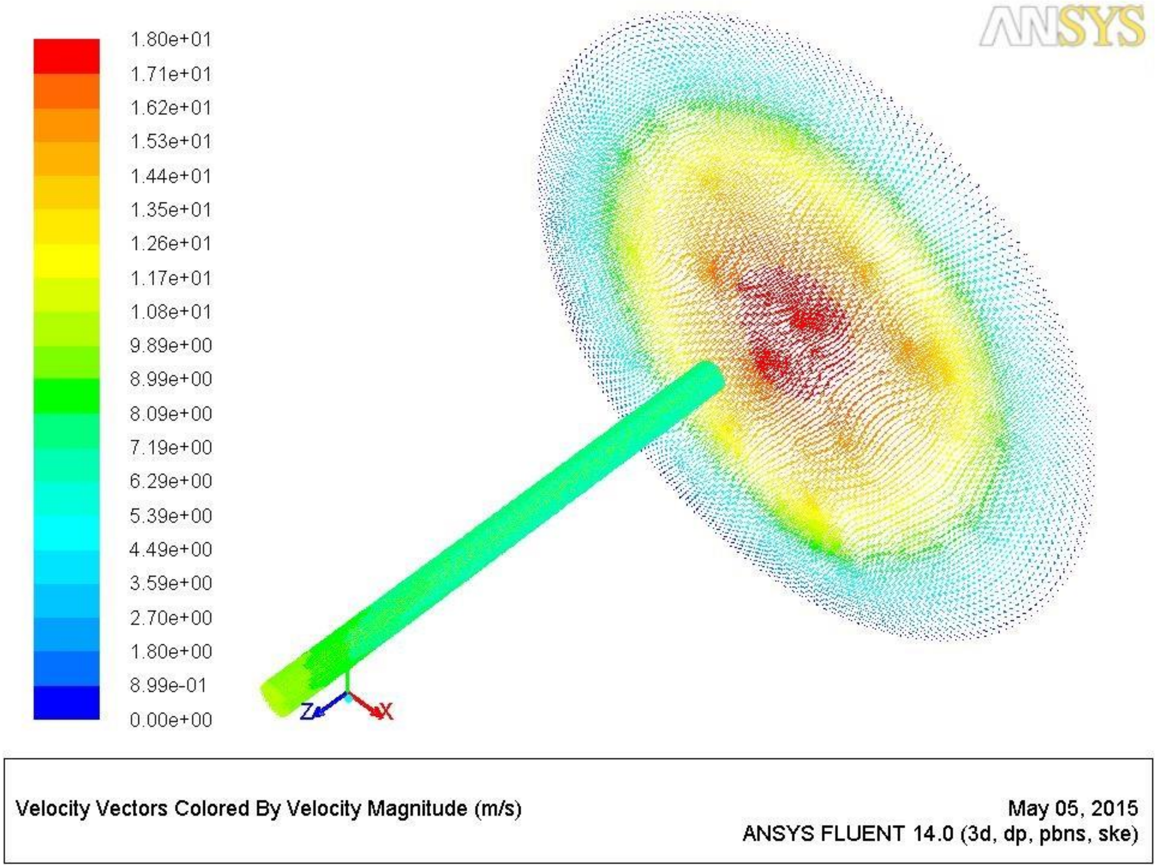

Fig 4.3 Velocity vectors colored by velocity magnitude

The above figure Fig 4.3 depicts the directions in which the velocity vectors are directed in the ECM process.

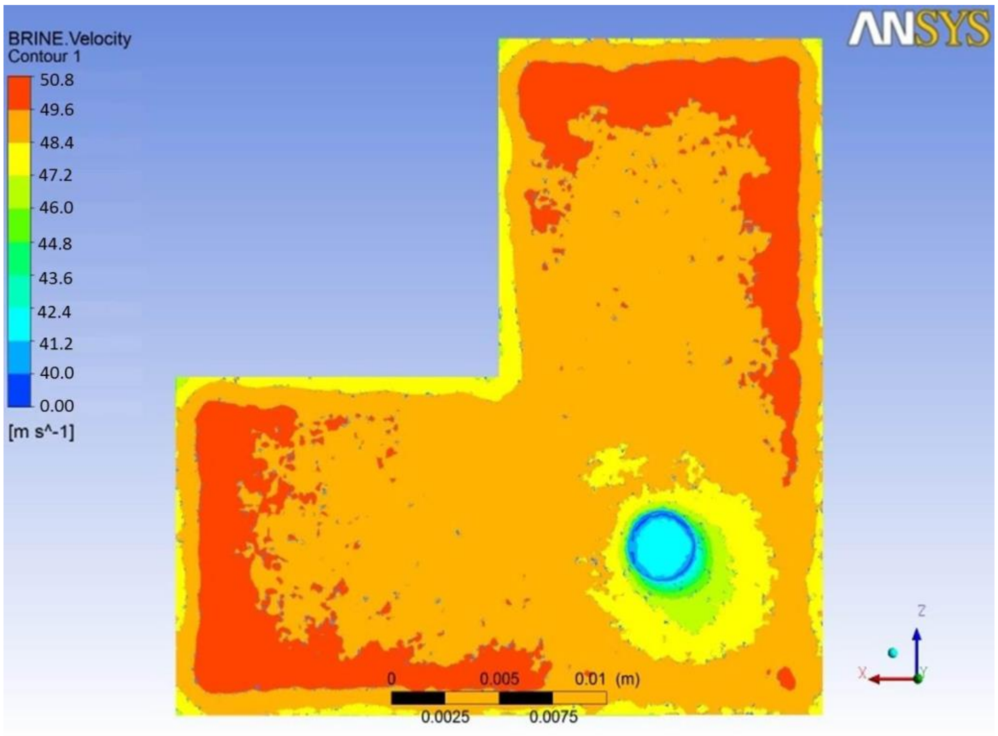

Fig 4.4 Electrolyte velocity contour

The above velocity contour shows that as the electrolyte moves from the circular through hole to the outskirts, the velocity of electrolyte flow increases most probably due to the increase in the flow area and also may be due to the hydrogen bubble formation.

4.3 PRESSURE PROFILES

Fig 4.4 shows the variation of the pressure of the electrolytic flow in the work piece tool interface when the velocity of flow through the inlet is 20m/sec.

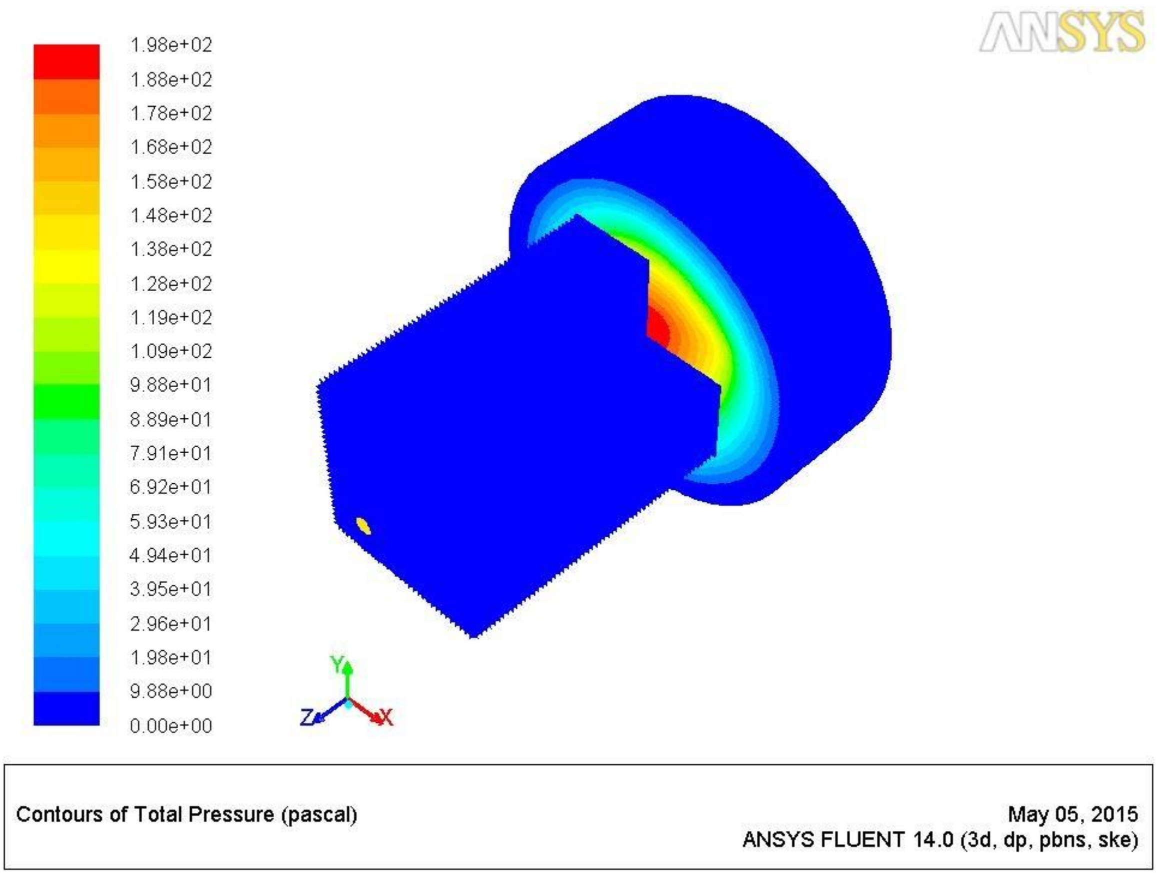

Fig 4.5 Contours of total pressure

The above figure represents the pressure contours in the tool work piece interface. The pressure is maximum at the center and gradually decreases as we move away from the central through hole.

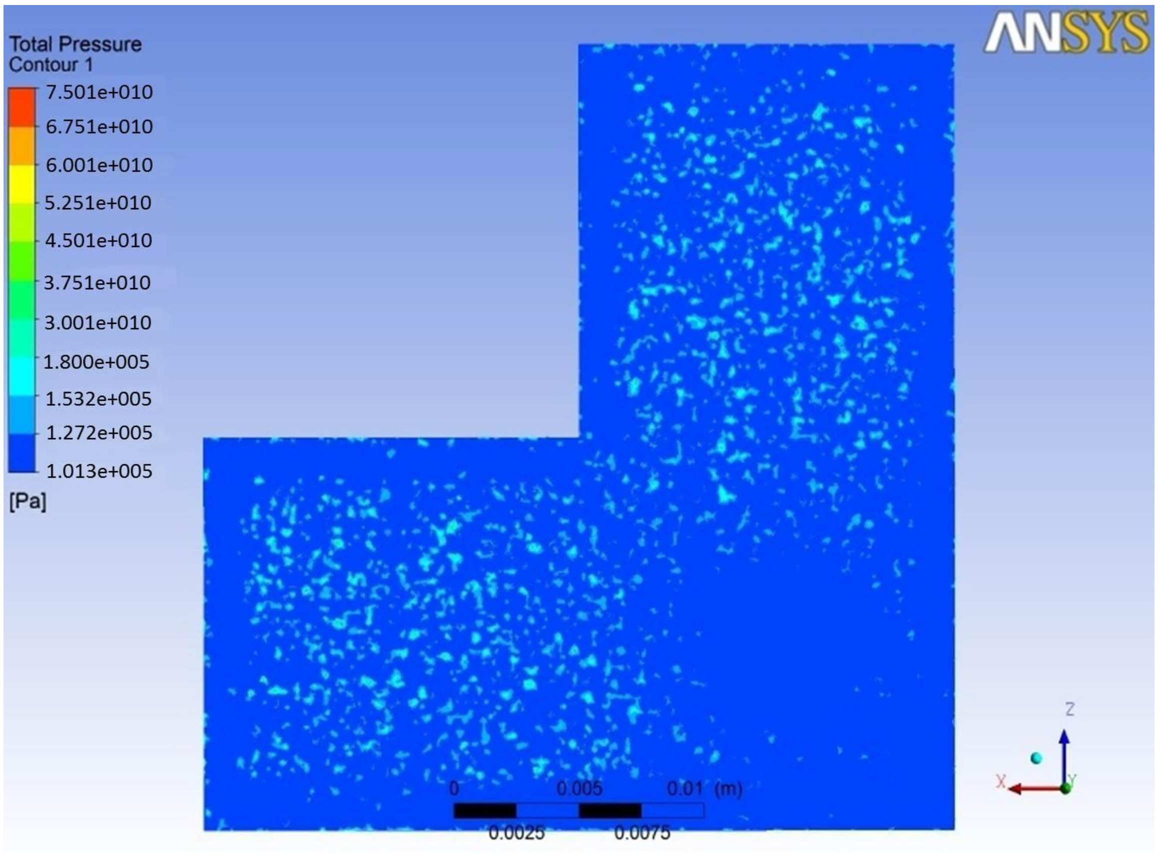

Fig 4.6 Total Pressure Contour

Variation of the total pressure during the machining process is depicted in the above figure. It is evident that due to the cavitation effect and due to formation of large number of hydrogen bubbles, the pressure value is not so specific but becomes higher at some nucleus sites away from the middle groove. The pressure at the boundaries is higher due to the presence of hydrogen bubbles at the sites and hence the pressure is high at those points.

4.4 TEMPERATURE PROFILES

The figure below shows the patterns in which the temperature varies in the work piece electrolyte interface during the course of machining.

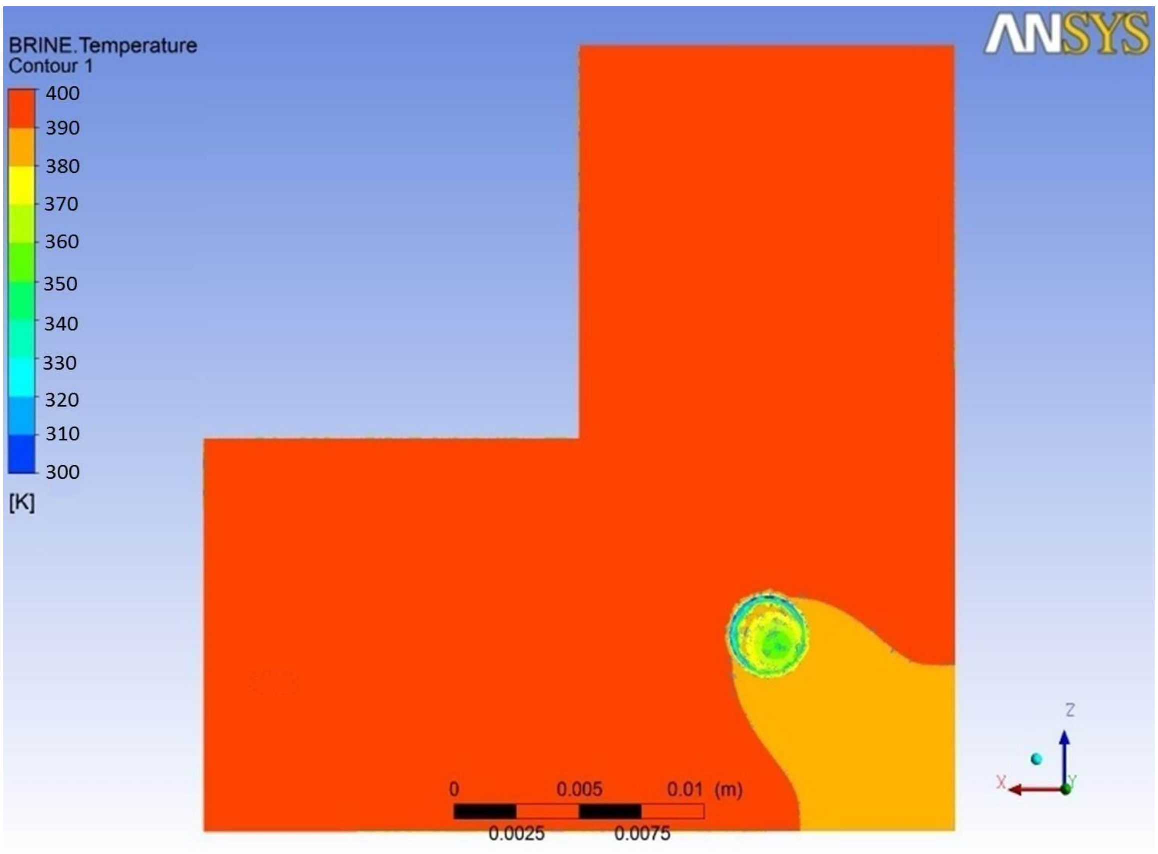

Fig 4.7 Temperature Variation contour

The temperature profile shown above is one of the most important aspects of the ECM analysis. From the above figure it is evident that the temperature of the electrolyte is minimum at the points nearest to the through hole and it increases as the distance from the groove increases. As the temperature increases it gradually crosses the boiling point of brine and hydrogen gas bubbles originate. This gives rise to the secondary phase phenomenon.

4.5 TURBULENT KINETIC ENERGY PROFILE

The figures below depict the turbulent kinetic energy profile during the ECM machining process. As in this investigation, we have considered k-ϵ model for the turbulence, so there is a variety in k and also in ϵ for a variety in the turbulence. Turbulence in the k- ε model relies on upon 95 turbulent active vitality (k) and turbulent vortex dispersal (ε). Unpleasantness of the machined surface has an immediate connection with the turbulence. Turbulent active vitality delineates the vitality in the turbulence. Turbulent active vitality is delivered by liquid shear, grating or lightness or through outer powers at low recurrence swirl. The turbulent kinetic energy worth is lower close to the score outlet and increments towards the external limits on account of more turbulence which may be because of the arrangement of hydrogen air pockets.

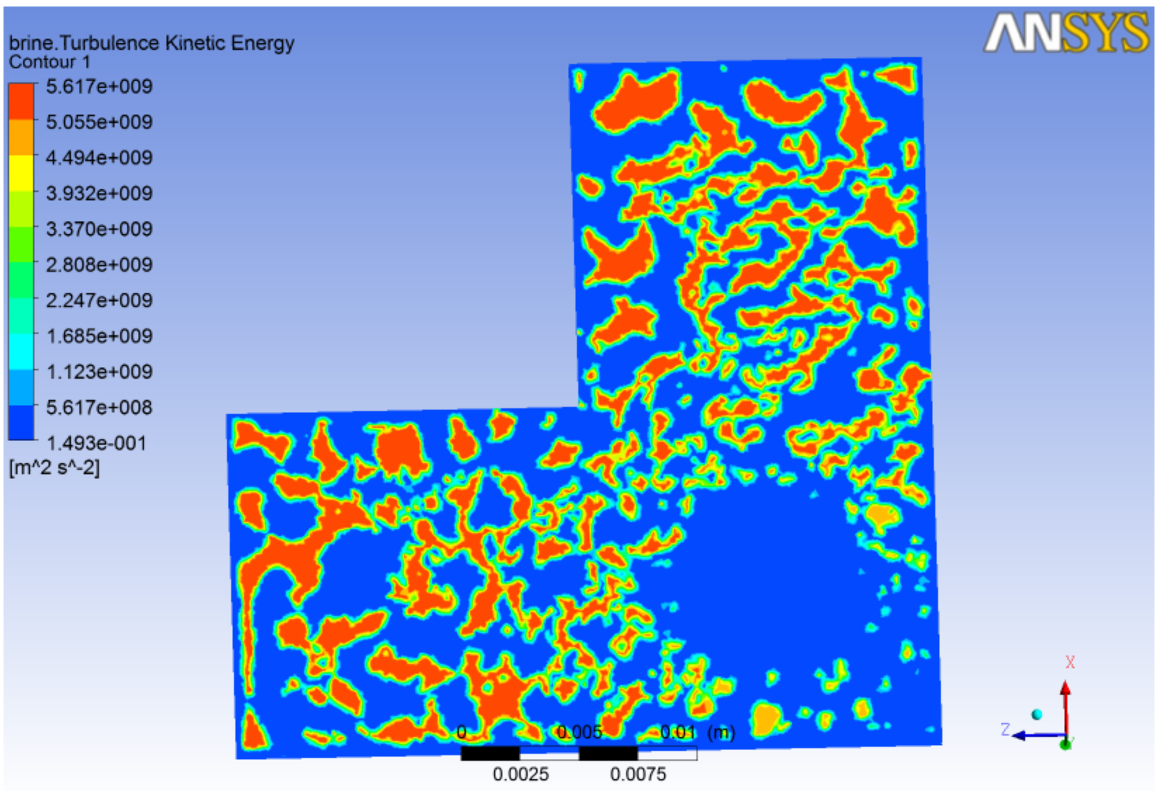

Fig 4.8 Turbulence Kinetic Energy

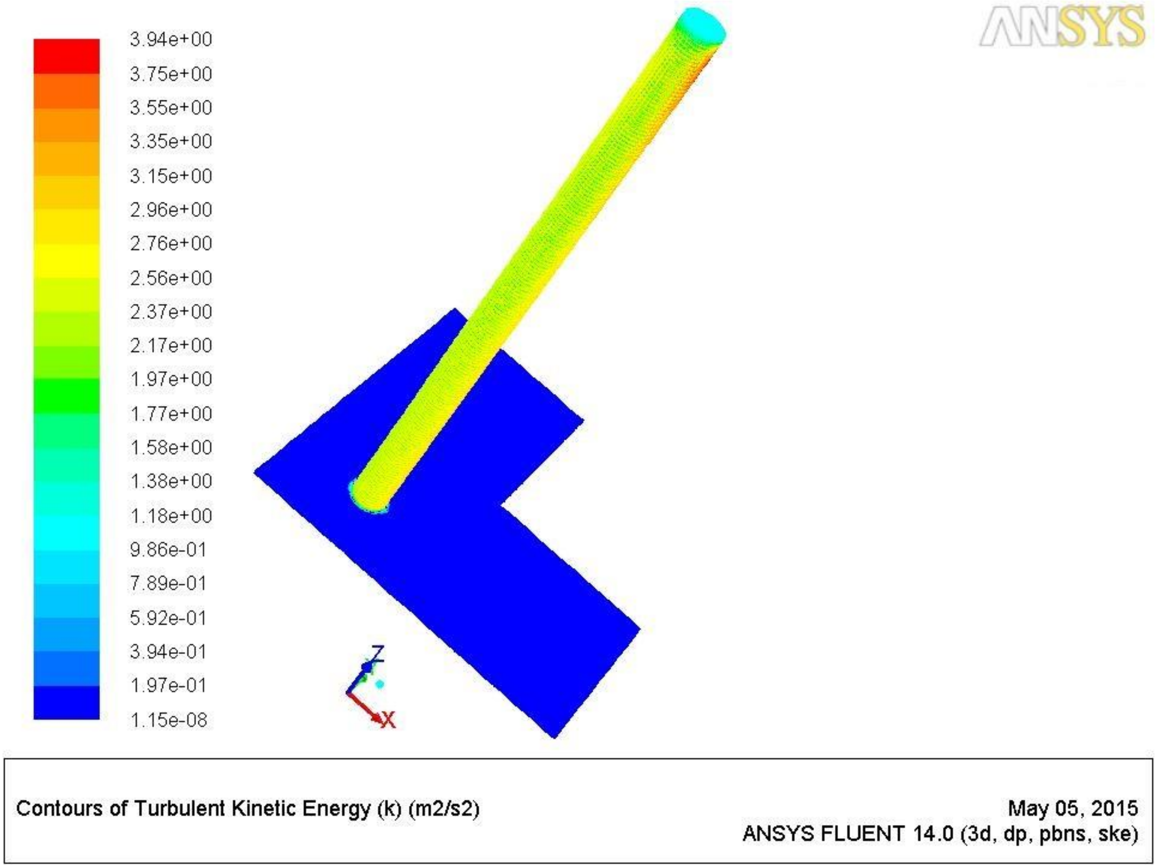

Fig 4.9 Contours of Turbulent Kinetic Energy

4.6 Heat Flux Pattern

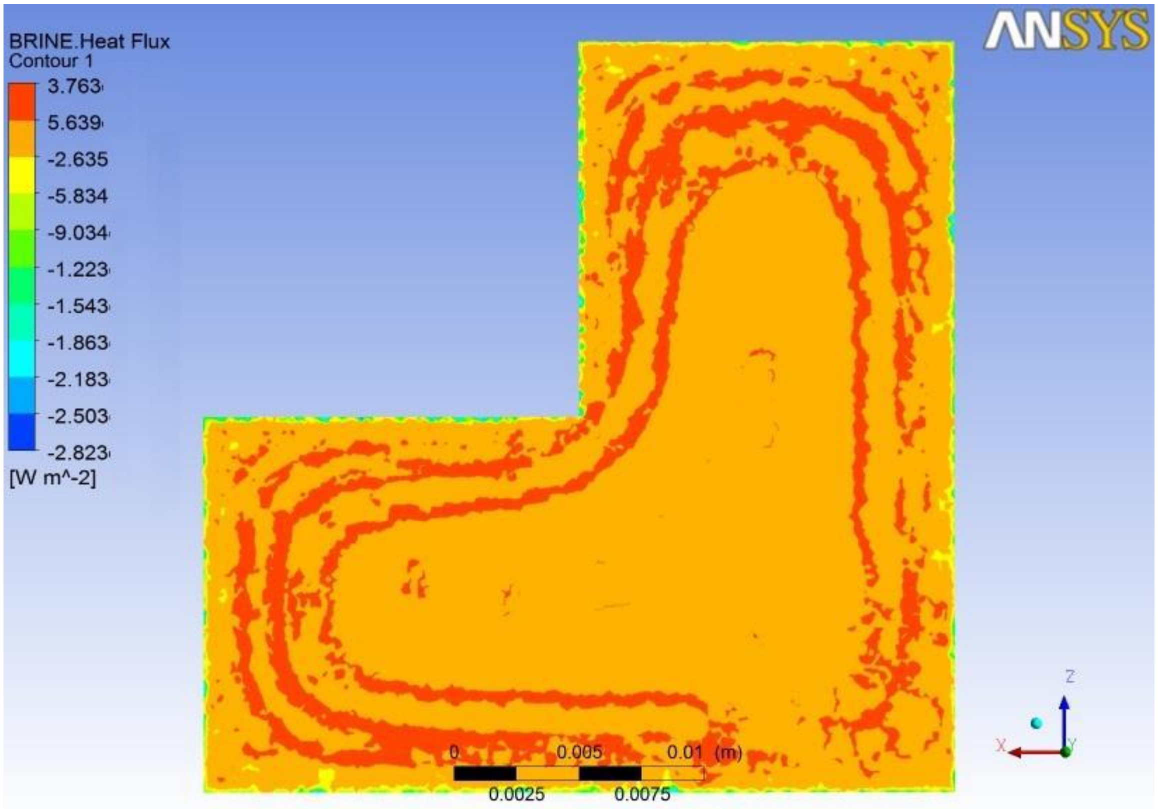

Fig 4.10 Heat Flux Pattern

In this simulation, we have accepted that the warmth created in the IEG is just because of Joule's Heating Effect. Heat flux is only the heat created in every unit machining zone. In the model, the worth is less close to the notch outlet. Be that as it may, as we continue towards the external, the warmth fluxes increments to a high sum. This higher estimation of warmth flux exists everywhere throughout the external limit of L shape in a relatively bigger territory.

4.7 SUMMARY

All the discriminating parameters in the IEG were introduced for all the Models. These parameters incorporate volume part of salt water, interphase mass exchange, velocity profile, weight profile, temperature profile, turbulent dynamic vitality profile, turbulent eddy dissipation profile and heat flux shape.

CHAPTER-5

CONCLUSION

5.1 INTRODUCTION

The two dimensional flow pattern in the Electrochemical Machining Process is very much useful in finding out the flow patterns, contours and the vectors of the important and useful parameters like velocity, temperature, pressure, heat flux, turbulence eddy distribution , turbulence kinetic energy etc. taking place in the inter electrode gap .Studying all these factors and their effect on the machining rate of the work piece gives a detailed idea about the parameters to be controlled and optimized.

5.2 CONCLUSIONS

1) With increase in the inlet current density, the velocity at the inlet of the tool increases proportionately.

2) The maximum temperature of the electrolyte comes down with the increment in velocity at the inlet of the tool. The highest outlet temperature decreases rapidly still in a particular velocity range the temperature change is not sudden. For the higher value of inlet velocity, temperature decreases abruptly.

3) The velocity of flow decreases as it moves through the through hole but on reaching the work piece the low velocity goes on increasing.

4) At the inlet to the tool the pressure in the highest this is minimum at the IEG.

5) .Temperature of the electrolyte may enter into the boiling point range which is evident due to the hydrogen bubbles formation.

6) Pressure increases at the nucleus sites on the work piece due to the presence of the hydrogen bubbles.

5.3 SCOPE FOR FUTURE WORK

1. There is a future scope for the simulation by applying tool motion.
2. Three phase flow analysis (brine solution, hydrogen bubbles and metal precipitation) is another area of research in future.

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